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Research Article

Keywords: Geoheritage assessment, Geotourism, Geopark, Geoconservation, Afar Depression, Ethiopia

Posted Date: November 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11361563/v1

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Additional Declarations: No competing interests reported.

Geoheritage Assessment of the Afar Depression, Northeastern Ethiopia: Foundations for Geotourism and Geopark Establishment.

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Abstract

Geotourism and Geoparks development represent an emerging interdisciplinary frontier in the field of geosciences, offering integrated pathways for geoconservation, geoeducation, and sustainable regional development. The Afar Depression of northeastern Ethiopia constitutes one of the planet's most geologically significant landscapes, characterized by exceptional geodiversity encompassing active volcanism, hydrothermal systems, rift tectonics, and paleoanthropological sites. Despite this outstanding natural endowment, the region's geoheritage remains largely uncharacterized and its geotourism potential unrealized. This study systematically identifies and assesses key geoheritage sites across the Afar Depression through an integrated methodology combining field investigations, satellite imagery interpretation, and systematic literature review. Geosites are evaluated according to their scientific, educational, aesthetic, adventure, and geo-health values, and classified at international, national, and local significance levels. Among the identified sites, Dallol hydrothermal field, Erta Ale lava lake, and the Middle Awash paleoanthropological corridor emerge as geosites of outstanding international value, meeting the foundational criteria for UNESCO Global Geopark designation. Although Ethiopia holds one of the highest concentrations of UNESCO World Heritage Sites in Africa, no national or UNESCO Global Geopark has yet been established. This study provides the scientific foundation for advancing geopark establishment in the Afar region and a replicable model for geoheritage assessment across geologically exceptional but underrepresented African territories.

Keywords: Geoheritage assessment · Geotourism · Geopark · Geoconservation · Afar Depression · Ethiopia

1. Introduction

1.1 Geodiversity, geoheritage and geoconservation: a global context

Geodiversity encompassing the natural range of geological, geomorphological, pedological, and hydrological features, processes, and systems underpins both ecosystem function and cultural identity (Gray, 2018). From this broader geodiversity foundation, geoheritage refers specifically to those components of the abiotic natural environment that carry outstanding scientific, educational, cultural, or aesthetic significance and merit targeted conservation (Brilha,

2016).Geoheritage conservation has progressively evolved from site-level protection toward landscape-scale governance frameworks, most prominently through UNESCO's Global Geoparks Programme.

Global Geoparks are defined as single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education, and sustainable development (UNESCO, 2016). Established in 2015 as an official UNESCO designation and as of 2026, 241 UNESCO Global Geoparks operate across 51 countries, yet the African continent remains dramatically underrepresented, with two designated sites across the entire continent (GGN, 2026). This disparity is particularly striking given that Africa hosts some of the world's most exceptional geological and paleoanthropological landscapes, many of which remain scientifically undocumented and institutionally unprotected.

1.2 Geotourism as a tool for geoheritage promotion

Geotourism is a form of sustainable tourism that promotes and enhances the geological identity of a place while integrating its natural, cultural, and social heritage (Dowling, 2021). It has become an effective mechanism for translating geoheritage into geoeducational, environmental sustainability, and socioeconomic benefits for local communities (Reynard & Brilha, 2018). Within the UNESCO Global Geopark framework, geotourism serves as a key management tool that supports geoconservation, sustainable livelihoods, local identity, and climate-resilient regional development while ensuring the long-term protection of geoheritage resources (UNESCO, 2023; Dowling, 2021).

The systematic assessment of geotourism potential is a prerequisite for any geopark development pathway. Quantitative and semi-quantitative geosite evaluation methods including the Geosite Assessment Model (GAM; Pereira et al., 2007), the Modified GAM (M-GAM; Coratza & Giusti, 2005), and the Methodology for Assessing the Scientific and Additional Values of Geosites (Brilha, 2016) provide structured, replicable frameworks for ranking geosites according to their scientific, educational, and touristic values. The application of such methodologies to emerging geoheritage territories is critical for building the evidence base required for national and international geopark recognition.

1.3 The Afar Depression: a globally exceptional geoheritage territory

The Afar Depression of northeastern Ethiopia constitutes one of the most geodynamically active and scientifically significant landscapes on Earth. Situated at the convergence of the Nubian, Somali, and Arabian tectonic plates-forming the Afar Triple Junction- the region is a natural laboratory for the study of continental rifting, plate divergence, and the early stages of ocean basin formation (Hayward & Ebinger, 1996; Chorowicz, 2005; Varet, 2018). The Afar Depression is currently the only location on Earth, alongside Iceland, where an actively spreading mid-oceanic ridge system is exposed above sea level, making it an irreplaceable window into lithospheric and asthenospheric processes that are otherwise accessible only through submarine investigation (Wolfenden et al., 2005; Varet, 2018).

The region's geological significance extends well beyond tectonics. Active volcanism- most visibly expressed at Erta Ale, one of the world's few persistent lava lakes-is accompanied by extraordinary hydrothermal activity at Dallol, where one of Earth's most extreme surface environments has produced a globally unique assemblage of hydrothermal mineral deposits, acidic brine pools, and salt formations (Cavalazzi et al., 2019). The Danakil Depression, at approximately 125 meters below sea level, represents one of the lowest and hottest permanently inhabited places on Earth, hosting evaporite sequences of considerable mineralogical and stratigraphic significance. These volcanic and hydrothermal features, combined with the region's active fault systems and seismicity, render the Afar Depression a site of exceptional geodiversity across multiple Earth science disciplines.

Equally significant is the Afar Depression's contribution to paleoanthropology. The Middle Awash research area has yielded some of the most consequential hominin fossil discoveries in scientific history, including *Ardipithecus ramidus* at Ardi, *Australopithecus afarensis* at Hadar-famously represented by the specimen known as Lucy and the world's oldest documented stone tools at Gona (Johanson et al., 1982; White et al., 2009; Semaw et al., 2003). These discoveries have fundamentally shaped understanding of human evolutionary origins, conferring on the Afar Depression a paleoanthropological significance that extends far beyond geological value alone.

2. General Description of the Survey Area

2.1 Geographic Setting and Administrative Context

The Afar Depression is situated in northeastern Ethiopia and constitutes the northernmost segment of the East African Rift System (EARS). It forms within the extensional zone defined by the divergence of three major lithospheric blocks: the Nubian (African), Somali, and Arabian plates (Hayward & Ebinger, 1996). Geographically, the study area is bounded approximately between 554528-715545mE and 1271313-1603967mN in UTM Zone 37N (Fig.2.1). Administratively, it corresponds largely to the Afar Regional State of Ethiopia, one of the country's ten federal administrative regions, covering an area of approximately 270,000 km².

2.2 Population and Socio-economic characteristic

The region is home to the Afar people, a predominantly pastoral and agropastoral community whose livelihoods are closely tied to the region's distinctive landscape and natural resources, including artisanal salt and gold mining on the Northern Afar Depression a practice with centuries of cultural heritage. The population of the Afar Regional State is estimated at approximately 1.8 million (CSA Ethiopia, 2022), distributed across a vast and sparsely populated terrain.

2.3 Physiography

The Afar Depression is predominantly a lowland basin dissected by horsts and grabens, with isolated high-relief peaks representing Quaternary shield volcanoes and volcanic ranges. Elevation across the region varies dramatically, from approximately 125 meters below sea level in the Dallol Depression- one of the lowest subaerial surfaces on Eartht- to approximately 2,145 meters above sea level in the western highland margins (Fig. 2.2). This extreme altitudinal range within a relatively confined geographic area reflects the region's intense tectonic activity and produces highly contrasting physiographic zones, from basaltic lava plains and salt flats to fault escarpments and volcanic edifices.

2.4 Climate

According to moisture regime classification, the Afar Depression is characterized by hyper-arid to arid conditions across its central and northern sectors, grading into semi-arid conditions toward the southwestern margins. Mean annual temperatures consistently exceed 30°C across much of the lowland basin, with Dallol - in the northern Danakil Depression- holding the record for the highest mean annual temperature ever recorded for any inhabited location on Earth, averaging approximately 34.4° (WMO, 2024). Annual precipitation is extremely low, generally below 200 mm across the hyper-arid core, with most rainfall concentrated in two short wet seasons.

Monthly temperature variability is relatively modest compared to the marked seasonal variation in precipitation, which briefly moderates surface conditions during peak rainfall months. From a geotourism perspective, the period from November to February represents the most favorable window for visitor activity, combining lower temperatures with reduced precipitation and improved accessibility across the region's unpaved terrain.

2.5 Geological setting

The Afar Depression occupies the central junction of the Afro-Arabian Rift System, which comprises three interconnected rift arms: the southern Red Sea Rift, the Gulf of Aden Rift, and the East African Rift. These three rift arms converge to form a triple-junction zone approximately 400 km in width, with the Afar Depression at its focus (Hayward & Ebinger, 1996). This configuration makes the Afar one of the best-exposed natural laboratories on Earth for studying the transition from continental rifting to incipient oceanic spreading.

The Afar Depression is the only subaerial location on Earth - alongside Iceland - where an actively spreading mid-oceanic ridge system can be observed directly at the surface, allowing researchers to examine all successive stages of lithospheric divergence since the onset of continental breakup (Wolfenden et al., 2005; Varet, 2018). The region currently represents an advanced stage of continental-to-oceanic rift transition within the broader EARS framework, and is considered one of the most tectonically dynamic terrains accessible to geological investigation (Chorowicz, 2005; Varet, 2018; Rime et al., 2023).

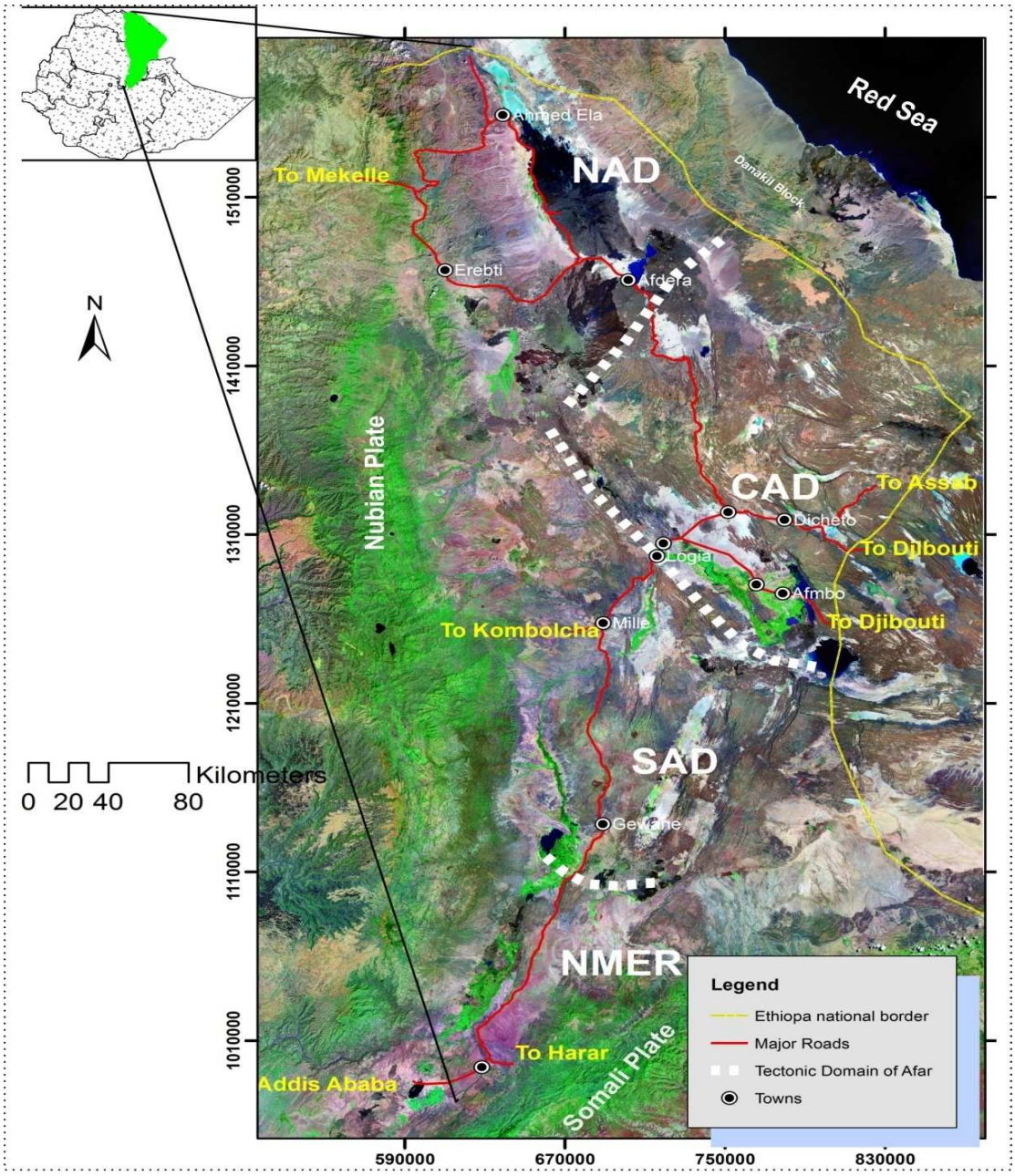


Figure 2.1 Location of the Afar Depression. Satellite image of the Afar Depression showing principal physiographic divisions. NAD, CAD and SAD denote Northern, Central and Southern Afar Depression respectively and NMER stands for Northern Main Ethiopian Rift

Active surface processes provide continuous and observable evidence of ongoing extensional deformation. These include frequent shallow seismicity, active normal faulting, episodic dike intrusion events, and persistent volcanism-most spectacularly manifested in the Erta Ale volcanic range, which hosts one of the world's longest-lived lava lakes and serves as a surface indicator of active magmatic plumbing at shallow crustal depths (Varet, 2018). The region's

geological record encompasses magmatic, volcanic, tectonic, sedimentary, and geodynamic processes operating across both continental and nascent oceanic lithospheric domains, rendering it a site of truly global geological significance.

The broader geological architecture of the Afar Depression is shaped by a mantle thermal anomaly - a major hotspot- whose upwelling drives the regional extensional regime and sustains the active volcanism and hydrothermal activity that characterize the region's surface expression (Varet, 2018). Hydrothermal manifestations are particularly striking at Dallol, where interaction between geothermal brines and evaporite sequences produces an assemblage of mineral precipitates, acidic pools, and salt structures of exceptional scientific and aesthetic interest.

Paleoanthropological significance

Beyond its geological distinction, the Afar Depression occupies a unique position in the history of human evolutionary research. The Middle Awash research corridor has yielded a series of hominin fossil discoveries that have fundamentally reshaped scientific understanding of human origins. These include *Ardipithecus ramidus* recovered at the Ardi site, representing one of the earliest known hominin species at approximately 4.4 million years before present (White et al., 2009); *Australopithecus afarensis* recovered at Hadar, represented most famously by the specimen designated AL 288-1 and popularly known as Lucy, dated to approximately 3.2 million years (Johanson et al., 1982); and the world's oldest documented stone tools at Gona, dating to approximately 2.6 million years (Semaw et al., 2003). Collectively, these discoveries establish the Afar Depression as one of the most significant paleoanthropological territories on Earth, a status that substantially amplifies its geoheritage value and geotourism appeal beyond what geological criteria alone would confer.

3. Methodology

This study employed an integrated, multi-phase methodology combining desktop analysis, remote sensing, systematic field investigation, laboratory analysis, and geotourism potential assessment. The methodological framework is organized into five sequential phases as described below.

3.1 Document review and data acquisition

3.1.1 Systematic literature review

A systematic review of published and unpublished literature was conducted to establish the scientific, geological, and geotourism context of the Afar Depression. Sources reviewed included peer-reviewed journal articles, theses, technical reports, and official policy documents pertaining to geoheritage assessment, geoconservation, geotourism development, and geopark establishment at national and international levels.

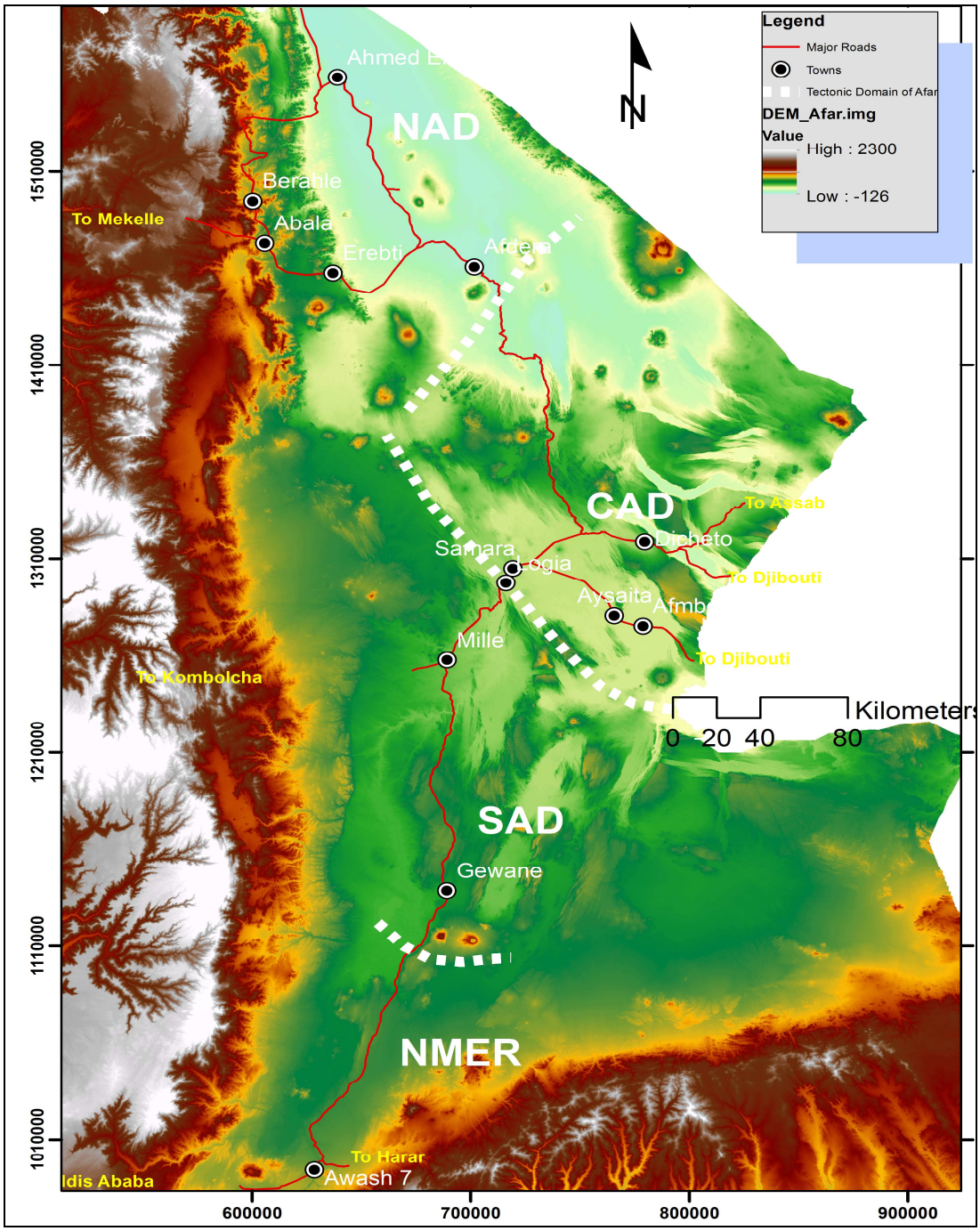


Figure 2.2. DEM of Afar Depression NAD, CAD, SAD and MER (separated by the white broken lines) are the northern, central and southern sectors of the Afar Depression and Maine Ethiopian Rift.

3.1.2 Remote sensing data acquisition and processing

Multispectral satellite imagery was acquired from publicly accessible repositories to support geological mapping, geosite identification, and landscape characterization. Landsat 8 and Sentinel-2 imagery were obtained from the United States Geological Survey (USGS) EarthExplorer and Copernicus data Space Ecosystem portal. Digital Elevation Models (DEMs), including the Shuttle Radar Topography Mission (SRTM) 30 m product and the ASTER Global Digital Elevation Model (ASTER GDEM), were used to analyze topographic characteristics, fault structures, volcanic morphology, and site accessibility. Supplementary aerial imagery was acquired from drone surveys conducted during field campaigns and from archive materials provided by partner institutions.

All remote sensing data were processed and analyzed using ArcGIS software platforms. Image compositing, band ratio analysis, and geological lineament mapping were applied to support field survey planning and post-field geosite characterization. Remote sensing outputs were integrated with field-collected GPS data and geological observations within a unified GIS geodatabase.

3.2 Field investigation

3.2.1 Field campaigns and geosite survey

Field investigations were conducted across multiple campaigns between 2021 and 2024, covering the principal geologically and geomorphologically significant zones of the Afar Depression. For each candidate geosite, the following data were systematically recorded: geographic coordinates (GPS), geological and geomorphological description, photographic documentation, evidence of existing visitor use, infrastructure conditions, conservation status, and any active threats to site integrity. A total of thirty one (31) geosites (Fig. 3.1) were surveyed and considered for inclusion in the final geoheritage inventory.

3.3 Laboratory analysis

Sample preparation

Water sample preparation and analysis were carried out at the Ethiopian Construction, Design, and Works Corporation laboratory, Addis Ababa, Ethiopia. Sample preparation followed standard filtration procedures (APHA Method 2540A) and acid digestion protocols (APHA Method 3030) as appropriate for the analytes of interest.

3.3.1 Analytical procedures

All water samples were analyzed in accordance with the 23rd edition of the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Full analytical parameters and corresponding methods are presented in Appendix

Table A. Analytical quality was maintained through routine calibration with certified reference standards, procedural blanks, and duplicate analysis, with a target precision of ±5% relative standard deviation.

3.4 Geoheritage and geotourism potential assessment

3.4.1 Geosite identification and inventory

Candidate geosites were identified through the convergence of remote sensing analysis, systematic literature review, and field observation. Sites were included in the inventory if they exhibited at least one of the following: outstanding scientific value in terms of geological, geomorphological, or paleoanthropological significance; high educational, exceptional aesthetic, potential geotourism appeal; or evidence of cultural or historical association with the geological landscape.

3.4.2 Assessment framework and scoring

The geotourism potential of each inventoried geosite was evaluated using a modified multi-criteria assessment framework adapted from established geosite evaluation methodologies (Brilha, 2016; Reynard et al., 2016; and Vereb et al., 2020). Each geosite was scored across five value categories:

Scientific value (Vs): geological uniqueness, representativeness, research history, integrity

Educational value (Ve): interpretive potential, accessibility for non-specialist visitors, didactic relevance

Aesthetic value (Va): scenic quality, visual diversity, landscape composition

Adventure and geo-health value (Vah): potential for active geotourism experiences, therapeutic or wellness associations with geothermal and mineral water features

Conservation value (Vc): current protection status, vulnerability to degradation, urgency of management intervention

Scores were assigned on a standardized numerical scale (typically as low, moderate and high) and aggregated to produce a composite geotourism potential index for each site (table 4.1). Based on composite scores and benchmarked against UNESCO Global Geopark criteria (UNESCO, 2016), geosites were classified into three significance tiers: International, national, and local. This classification informed both the prioritization of conservation interventions and the strategic geotourism development recommendations presented in Section 4. The assessment has been designed in order to minimize subjectivity. Each assessment framework categories were rated through a combination of literature review, comprehensive field campaigns and laboratory analysis.

4. Geoheritage Inventory and Assessment

The Afar Depression's exceptional geological setting supports a remarkable diversity of geosites encompassing active volcanic systems, hydrothermal fields, tectonic landforms, evaporite landscapes, and internationally significant paleoanthropological localities. This section presents the systematic inventory and multi-criteria geotourism potential assessment of the principal geoheritage sites identified across the study area. Sites are organized by genetic and thematic category, described in terms of their geological characteristics and geotourism attributes, and evaluated using the integrated assessment framework described in Section 3.4. A summary of assessment scores of geoheritage sites and significance classification for all inventoried geosites is presented in Table 4.1 and mapped in Figure 4.1.

Applying the five-category assessment framework (scientific value Vs; educational value Ve; aesthetic value Va; adventure and geo-health value Vah; conservation value Vc), geosites were ranked as high, moderate, or low geotourism potential and further classified by geographic significance as international, national, or local (Fig. 4.1). The identified geoheritage sites are organized into five thematic categories: (i) geothermal features, (ii) volcanic landforms, (iii) geomorphological landscapes, (iv) paleoanthropological localities, and (v) tectonic and structural phenomena. Each category is described and assessed in the subsections below.

Table 4.1 Geotourism potential assessment of key geoheritage sites, Afar Depressio

Geosite	**Category**	**Value Categories**					**Overall rating**	**Significance**
		Vs	Ve	Va	Vah	Vc		
Dallol hydrothermal field	Geothermal	★★★	★★★	★★★	★★★	High	Very High	International
Erta Ale volcano	Volcanic	★★★	★★★	★★★	★★★	High	Very High	International
Boina fumarole field	Geothermal	★★★	★★★	★★	★★	High	High	National
Alallobad geothermal field	Geothermal	★★★	★★★	★★★	★★	High	Very High	International

Tio geothermal field	Geothermal	★★★	★★★	★★	★★	High	High	National
Hadar (Lucy site)	Paleoanthropological	★★★	★★★	★★★	★★	High	Very High	International
Lake Abhe	Geomorphological	★★★	★★	★★★	★★★	High	Very High	International
Afar triple junction	Tectonic	★★★	★★★	★★	★★	Medium	High	International

Vs = Scientific value; Ve = Educational value; Va = Aesthetic value; Vah = Adventure/geo-health value; Vc = Conservation priority. ★★★ = High; ★★ = Moderate; ★ = Low.

Table 4.1 Geotourism potential assessment of key geoheritage sites, Afar Depression (continued).

Geosite	**Category**	**Value Categories**					**Overall rating**	**Significance**
		Vs	Ve	Va	Vah	Vc		
Afar rift escarpments	Tectonic/ Geomorphological	★★★	★★★	★★	★★	Medium	High	International
Awash water fall and canyon	Tectonic/ Geomorphological	★★	★★	★★★	★★	Medium	Moderate - High	National
Lake Gameri and Afambo	Geomorphological	★★	★★	★★★	★★	Low	Moderate - High	National
Lake Loma	Tectonic/Geomorphological	★★★	★★	★★★	★★	Low	High	National

Abida Caldera/Crater	Tectonic/ Geomorphological	★★★	★★	★★	★★★	Low	High	Local
Tendahoo Dame	Geomorphological	★★	★★	★★	★	High	Moderate	Local

Vs = Scientific value; Ve = Educational value; Va = Aesthetic value; Vah = Adventure/geo-health value; Vc = Conservation priority. ★★★ = High; ★★ = Moderate; ★ = Low.

4.1 Geothermal Features

Geothermal activity in the Afar Depression is one of the most geologically dynamic and visually spectacular expressions of the region's position at an active rift triple junction. Surface manifestations-including hot springs, fumaroles, mud pools, hydrothermal mineral deposits, and acidic brine systems-occur at multiple locations across the Northern, Central, and Southern Afar Depression (Fig. 4.1). Three principal geothermal geosites of geotourism significance are assessed below.

4.1.1 Dallol hydrothermal field

General Description of Dallol area

The Dallol hydrothermal field occupies the northern sector of the Afar Depression, within one of the most geochemically extreme surface environments on Earth. The Dallol Depression covers an area of approximately 3 km², bounded by the Balakia Mountains to the west, the Danakil Alps to the northeast, and the Erta Ale volcanic range to the south (Fig. 4.6). Dallol Mount is located at the center of the rift axis of the Dallol Depression. At approximately 126 m below mean sea level, with mean annual temperatures of approximately 34.4°C and annual precipitation typically below 50 mm, Dallol ranks among the hottest, lowest, and most arid permanently accessible surface environments on Earth (Fazzini et al., 2015). The area is accessible via the Samara-Afdera-Ahmed Ela road corridor (approximately 320 km from Samara) or alternatively via the Samara-Afdera-Abala-Berahle route (approximately 420 km).

Hydrothermal system

The Dallol hydrothermal system results from the interaction of deep-circulating geothermal brines with the thick Quaternary evaporite sequences of the Danakil Basin. The system is highly dynamic: individual spring sites become inactive and new discharge points emerge over periods of days, while flow rates and chemistry vary over hours within a single site (Kotopoulou et al., 2019). Hydrothermal brines discharge as oxygen-free, hyperacidic, iron-rich fluids supersaturated with respect to halite, generating near-instantaneous precipitation of halite pillars reaching several meters in height upon surface exposure (Kotopoulou et al., 2019).

Major element concentrations in spring brines and hot pools are dominated by chloride (285.3 g/L) and sodium (46.8 g/L), followed by magnesium (35.8 g/L), calcium (21.4 g/L), iron (19.2 g/L), and potassium (9.3 g/L). Among trace elements, mercury (1,080 mg/L) and manganese (538 mg/L) are most abundant.

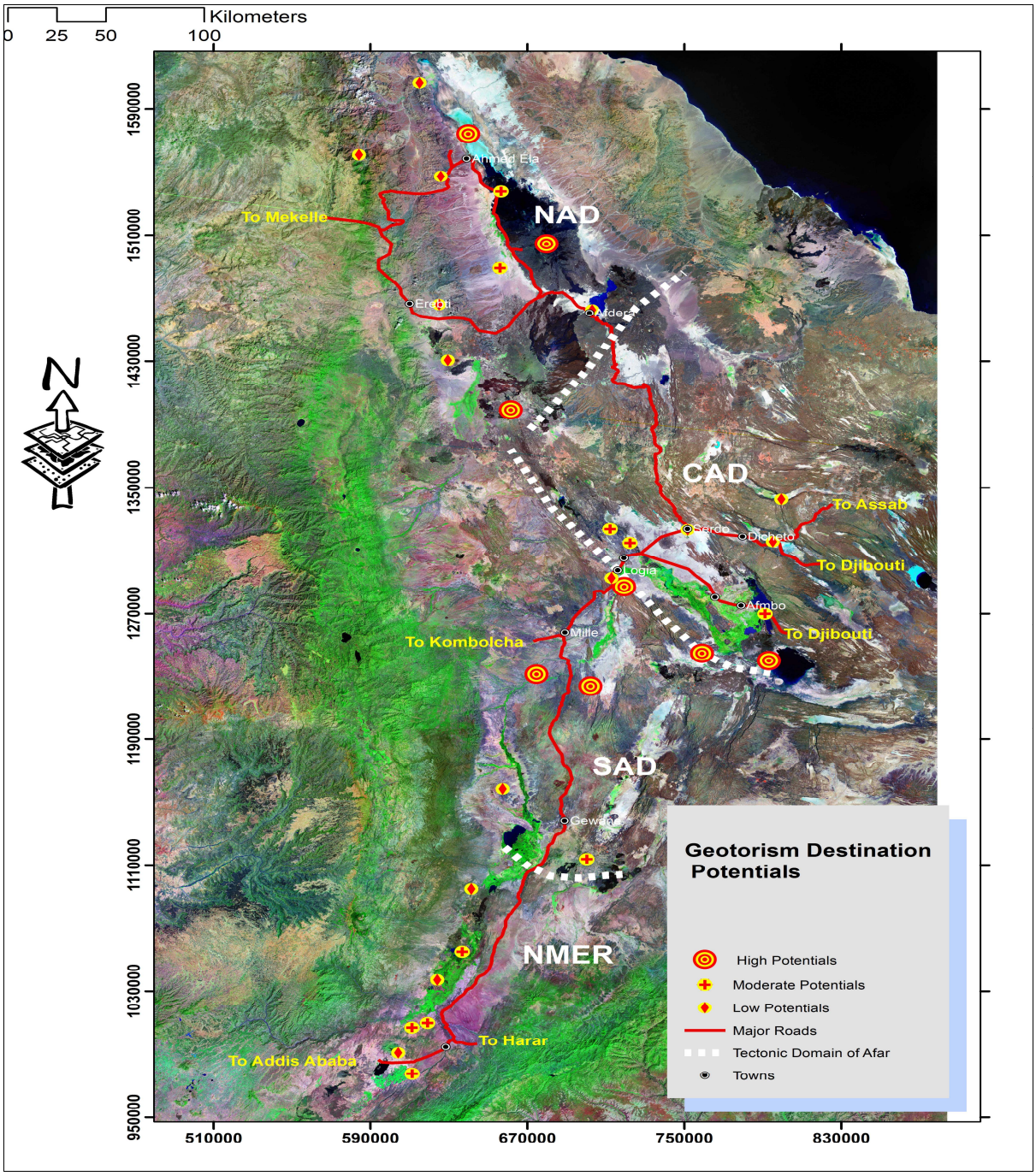


Figure 4.1 Geotourism Map Guides of the Afar Depressions. NAD, CAD, SAD and MER (separated by the white broken lines) are the northern, central and southern sectors of the Afar Depression and Maine Ethiopian Rift.

Aesthetic and geomorphological character

Dallol's surface is characterized by a striking assemblage of naturally sculpted salt canyons, mushroom-form halite structures, ropy brine surfaces, salt flower precipitates, polychromatic brine pools, acidic hot springs, and fumarole fields (Fig. 4.2). The chromatic diversity of the brine pools - spanning yellow, green, orange, and red tones - results from the combined effects of iron oxidation and mineral self-organization, extreme pH and redox gradients, and microbial pigmentation by carotenoid-producing microorganisms including cyanobacteria (Cavalazzi et al., 2019). The CNN designated the Danakil area as one of the world's fifteen most colorful landscapes in December 2014, reflecting the exceptional aesthetic quality that draws international visitors despite the site's extreme conditions.

Astrobiology and planetary science significance

Beyond its terrestrial scientific value, the Dallol hydrothermal field has been recognized as one of Earth's most relevant analog environments for the study of extraterrestrial habitability. The co-occurrence of active volcanism, diffuse hydrothermalism, extensive sulfate deposits, and hyperacidic conditions closely parallels inferred past hydrothermal environments on Mars, making Dallol an internationally significant planetary field analog for astrobiology research (Cavalazzi et al., 2019). This dimension adds a unique global scientific dimension to the site's geoheritage value that extends well beyond conventional geotourism categories.

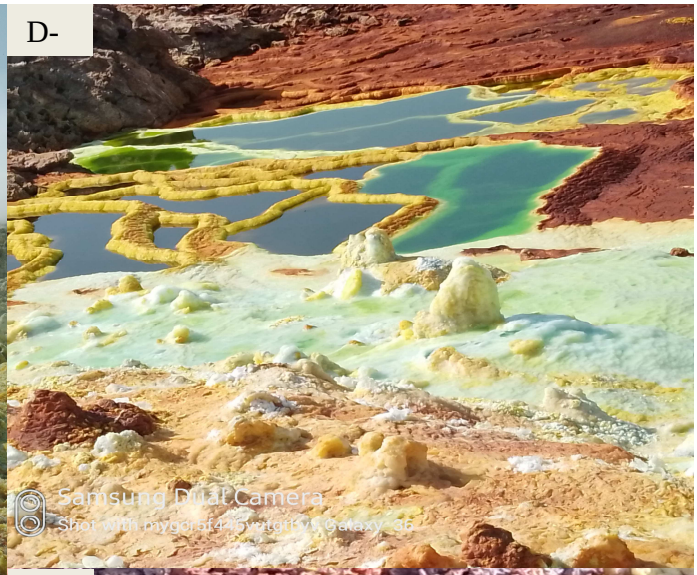
Geotourism assessment and significance

Dallol is assessed as a geosite of **International significance** across all five evaluation criteria: it represents a globally unique geochemical environment (Vs = high), offers exceptional interpretive potential for Earth science and astrobiology education (Ve = high), presents extraordinary aesthetic appeal (Va = very high), provides an extreme adventure geotourism experience (Vah = high), and faces significant geoconservation challenges from unregulated visitor access and the inherent fragility of evaporite surface structures (Vc = high priority). Dallol fulfils multiple criteria for UNESCO Global Geopark designation and represents the highest-priority geosite in the Afar Depression inventory for international geopark development.

D-


Samsung Dual Camera
Shot with mygcr5f445vutgtbyv Galaxy 36

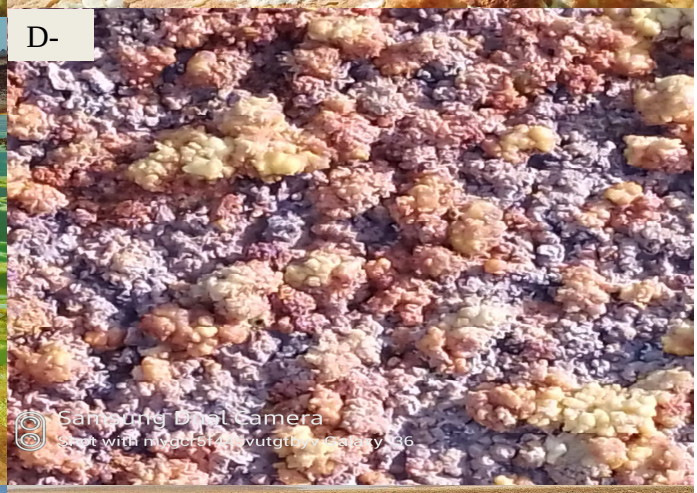
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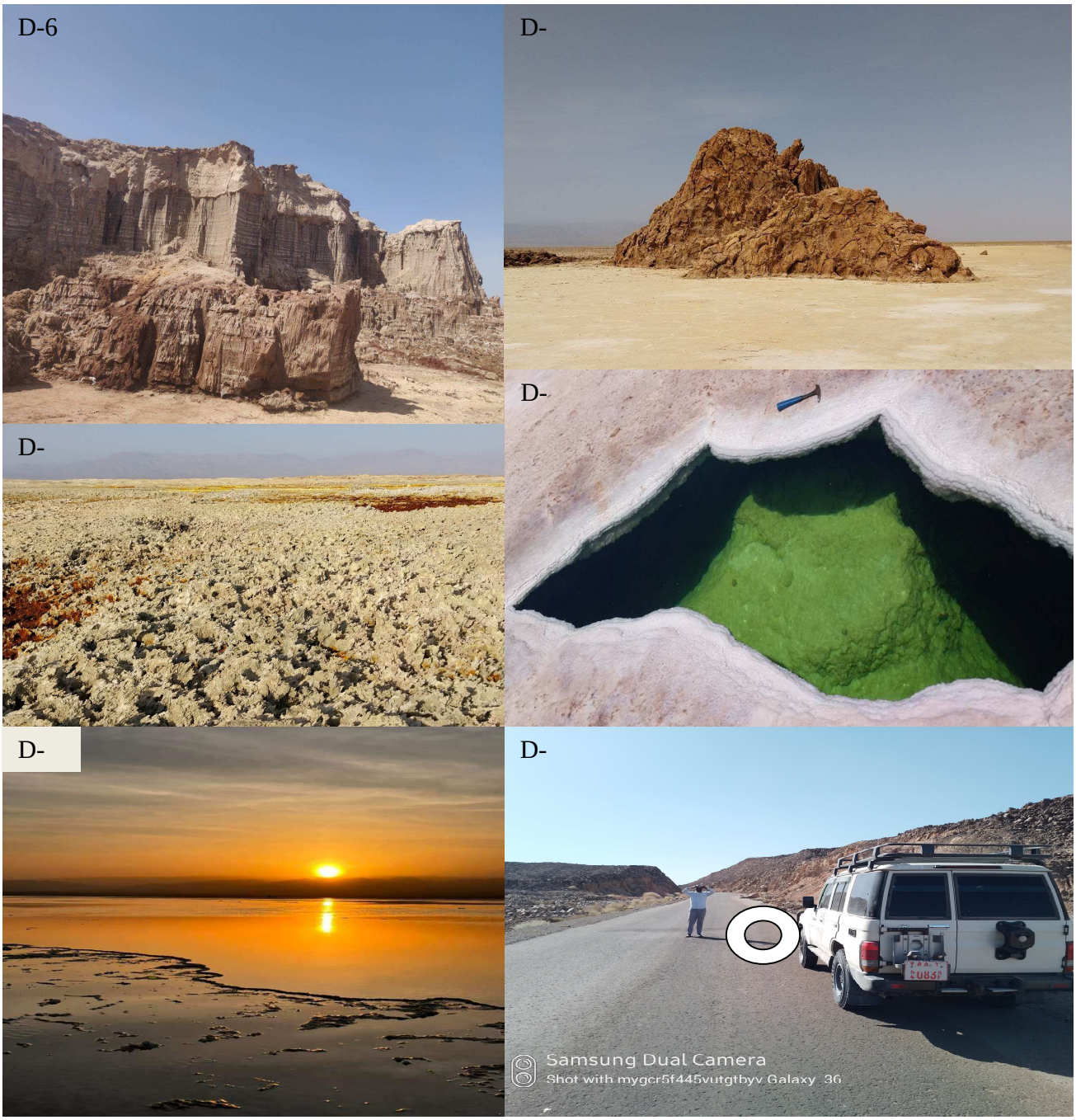

Samsung Dual Camera

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Figures 4.2 Representative image of the hydrothermal system and morphological features of Dallol area. D-4- Fumarols; D-5-Acidic Pools and Terraces; D-6-Salt Pillar-with clay and gypsum intercalation; D-10 Sun set activities; D-11 0 m altitude.

4.1.2 Alallobad and Tio geothermal fields

Geological and geothermal setting

Alallobad geothermal field is situated in the Central Afar Depression, approximately 21 km south of Samara (the capital of Afar Regional State), within the axis of the NW-SE trending Tendaho Graben. The site is currently at the feasibility stage of geothermal energy development (Geological Survey of Ethiopia, 2009). The Tendaho mountain range, forming a prominent fault scarp to the west of the field, is characterized by steam emanations and cold spring discharge, which drain downslope toward the active hydrothermal zone. Spring pool depths reach approximately 50 m at certain locations, with water temperatures measured between 69 and 99°C at Alallobad.

Tio geothermal field lies at the foothills of the Tendaho Mountain range in the Central Afar Depression, approximately 20 km east of Adaytu Town and south of Alallobad. Hot springs at Tio discharge at temperatures ranging from 81 to 98°C along the northeastern margin of the stratoid basaltic series, within the western extent of the Kereyyu Graben.

Both fields are characterized by structurally controlled hydrothermal systems hosted within Quaternary basaltic sequences, where geothermal fluids migrate along graben-bounding faults and extensional fracture networks. Surface expressions at both sites include hot spring pools of exceptional chromatic diversity - displaying green, sky-blue, and yellow coloration - fumarole fields, mud pools with pulsating discharge behavior, geysers reaching 0.5 to 6 m in height, and hydrothermally altered ground with fragile salt and sulfur crusts (Fig. 4.3 and 4.4).

Hydrogeochemistry

Water samples collected across both sites (n=33; 2021-2024) reveal a predominantly NaCl hydrochemical facies with elevated SO_4 and SiO_2 concentrations and an average total dissolved solids (TDS) content of approximately 7,220 mg/kg. A secondary bicarbonate water type ($NaHCO_3$ composition) with medium to moderately alkaline pH values (6.60–8.56) was also identified. The chromatic diversity of the spring pools reflects variations in mineral content - including arsenic, sulfur, silica, and calcium carbonate - together with the presence of thermophilic microorganisms such as cyanobacteria and algae, whose pigment expression is modulated by pH, temperature, and light intensity (Pecoraino et al., 2025).

The color of individual pools is thus determined by the specific combination of mineral precipitation, temperature regime, pH conditions, and microbial community composition - making each pool a visually distinct and scientifically significant microenvironment.

Geo-health significance and public health risk

The geothermal waters of both Alallobad and Tio have been traditionally used by the local Afar community for therapeutic purposes, including treatment of skin conditions, musculoskeletal disorders, and respiratory ailments.

Medicinal constituents identified through geochemical analysis include calcium (11,286 mg/L), sodium (17,248.5 mg/L), magnesium (6,019.2 mg/L), potassium (2,211.5 mg/L), sulfate (893.6 mg/L), and bicarbonate, alongside trace elements - including zinc, copper, iron, and selenium - reported by community members to benefit livestock milk production and overall animal health.

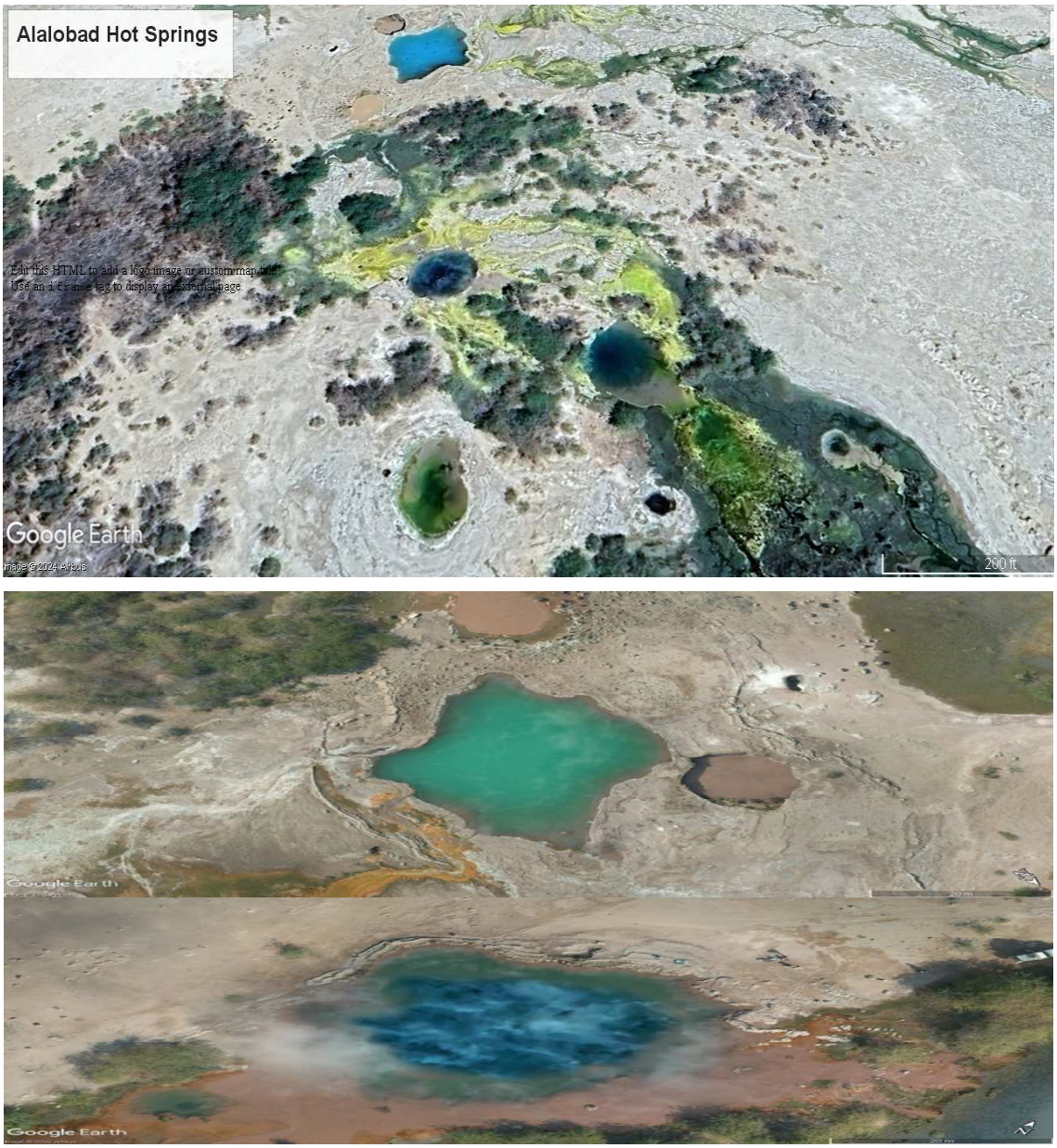
However, geochemical analysis also revealed concentrations of several elements substantially exceeding WHO drinking water guidelines. Arsenic concentrations ranged from 4.45 to 7.71 mg/L (WHO guideline: 0.01 mg/L), fluoride was measured at 37.02 mg/L (WHO guideline: 1.5 mg/L), and mercury ranged from 3.86 to 10.5 mg/L (WHO guideline: 0.006 mg/L). Qualitative community interviews confirmed health concerns consistent with chronic exposure to these elements, including dental and skeletal fluorosis, gastrointestinal disorders, and suspected long-term toxic effects. These findings underscore the critical importance of geochemical risk communication as part of any geotourism management framework for the site.

Additionally, active fumarole venting, unstable hydrothermally altered ground, deep pool margins, and mud eruption events present physical safety hazards for visitors. Formal geotourism development at both sites will require comprehensive visitor safety protocols, barrier infrastructure, and guided access management.

Geotourism assessment and significance

Despite its geotourism potential, Tio remains largely unknown beyond the regional research community, where formal geotourism infrastructure remains absent at the site. Alallobad has received initial recognition - including the construction of a connecting access road (Logia–Alallobad) and currently developing visitor infrastructures. The combination of exceptional aesthetic appeal, geo-health tradition, scientific significance, and adventure potential places both sites among the priority candidates for geotourism development and geoconservation planning in the Central Afar Depression.

Alallobad geosite are assessed as **International significance** across all evaluation criteria, whereas the Tio site is classified as **national significance** in terms of geotourism potential, with prospects for elevation to international significance pending further systematic characterization, formal geoconservation management, and promotional development. Development of georesort infrastructure, interpretive signage, and guided visitor programs is recommended as a priority management action.



Figures 4.3 Satelite image (Geogle image Pro) and Drone Image (Google earth 2025) of Alallobad Hot Springs-Centaral Afar Depression.



Figures 4.4 Field Photographs: Hot spring and mud pools, Fumaroles and gysure at the base of the fault scarp, altered grounds and hot spring pools with depth measurment of Central Afar Geothermal Fileds. Photos was taken looking westward

4.1.3 Boina (Dabbahu) fumarole field

Geological setting

The Boina fumarole field is situated near the summit of the Dabbahu volcanic complex in the Northern Afar Depression (UTM: 661564N, 1399202E), approximately 2 km northwest of the Dabbahu summit. The area comprises hydrothermally altered Quaternary volcanic deposits - including rhyolites, trachyte, pumice, and basalt - that host numerous active pit craters and fumarole vents (Fig. 4.5). A prominent NW–SE trending fissure system on the northwestern flank of the crater field aligns with the general orientation of the Tendaho Fault, indicating structural control on fumarolic degassing (Varet et al., 2018).

Surface expressions include sulfur-degassing fumaroles with visible sulfur staining on altered ground surfaces, inferred caldera structures, and fissure vent systems. Local communities have adapted lower-temperature fumarole vents as condensation sources for drinking water by constructing simple collection structures from rocks, grass, and wood - a traditional practice that simultaneously reflects the site's geo-cultural significance and constitutes a serious public health concern.

Hydrochemical risk

Geochemical analysis of waters collected from community condensation points at Boina (2024) revealed concentrations of fluoride (12.4 mg/L; WHO limit: 1.5 mg/L), arsenic (5.6 mg/L; WHO limit: 0.01 mg/L), and mercury (15.4 mg/L; WHO limit: 0.006 mg/L) far exceeding safe thresholds for drinking water consumption (WHO, 2022). Chronic exposure to these concentrations carries documented risks of cancer, kidney and liver damage, neuromuscular impairment, and skeletal fluorosis (US EPA, 2001). Community health risk communication and provision of alternative safe water sources constitute urgent management priorities at this site.

Geotourism assessment and significance

Boina is assessed as a geosite of **national significance** for geotourism, combining exceptional volcanic and hydrothermal features with geo-cultural and scientific dimensions rarely encountered at a single site. Its alignment with active fissure systems, inferred caldera structures, and evidence of ongoing degassing make it a site of high scientific value (Vs = high). Its relative accessible and limited current visitor infrastructure - accessible via the Samara-Teru route (approximately 150 km) or the Samara–Korry junction–Afdera–Teru asphalt road (approximately 260 km) - simultaneously represent geotourism development opportunities and geoconservation advantages.



Figures 4.5 Satellite image (Google Earth Pro); Active pit craters with fumaroles; “Boina” (i.e. fumaroles adapted by the local people to condense drinking water) and Fissure vent with sulfur stained and degassing.

4.2 Geomorphological Landscapes

The geomorphological diversity of the Afar Depression reflects the complex interplay of tectonic activity, volcanic construction, climatic aridity, and eustatic sea-level change operating across multiple timescales (Migon, 2009). The region's position at an active rift triple junction means that tectonic forcing remains the dominant control on landscape evolution, expressed through the formation of horsts, grabens, fault escarpments, and volcanic edifices that define the regional physiography. Superimposed on this structural framework, aeolian, fluvial, and lacustrine processes operating under hyper-arid to arid conditions have generated a secondary suite of landforms of considerable geotourism interest. The principal geomorphological geosites identified in the inventory are assessed below.

4.2.1 Volcanic Landforms

Volcanism is the most visually dramatic and scientifically distinctive element of the Afar Depression's geoheritage. The region hosts numerous volcanic edifices spanning shield volcanoes, stratovolcanoes, and calderas, with varying levels of current activity. The following subsections assess the principal volcanic geosites identified in the inventory.

Erta Ale shield volcano

Geological and volcanological setting

Erta Ale is a basaltic shield volcano rising from the floor of the Northern Afar Depression, constituting one of the most volcanologically significant active volcanic systems on Earth. Its summit is defined by an elliptical caldera elongated NNW-SSE (approximately 1,600 × 700 m), within which two pit craters have hosted persistent lava lake activity since at least 1967, and possibly since as early as 1906 (Barberi & Varet, 1970; Varet, 2018). This sustained multi-decadal lava lake activity places Erta Ale among a globally exclusive set of persistent lava lake systems, comparable only to Nyiragongo (Democratic Republic of Congo), Ambrym (Vanuatu), and Mount Erebus (Antarctica).

Historical records document significant variability in lava lake level and activity. The northern pit crater hosted an active lava lake until solidification occurred between 1988 and 1992 following emplacement of lava flows during that period (Varet et al. 2018). The southern pit lake experienced brief surface solidification between late 2004 and April 2005 before reactivation in September 2005, interpreted as a response to the regional volcanoseismic crisis of that year (Ayele et al., 2007). A significant overflow event from the southern pit onto the main crater floor was documented in November 2010 - the first recorded since a comparable event in March 1973 (Field et al., 2012).

Current activity and field observations

Field observations conducted in February 2024 recorded no active lava lakes within the main caldera. Three active scoria cones - distributed across the northeastern, eastern, and south-central sectors of the caldera floor along an NNW-aligned axial zone - were documented, with limited lava effusion from each (Fig. 4.6). Sulfurous degassing from the northeastern cone was recorded during the survey. Lava textures observed on fresh flow surfaces were glassy and porphyritic in character, with plagioclase and olivine phenocrysts in a fine-grained matrix, consistent with typical Erta Ale basaltic compositions, and displaying dominantly pahoehoe surface morphology.

Subsequent activity reported in September 2025 included lava fountaining, lava lake rise, and overflow events reaching the caldera rim (Fig. 4.7). Satellite imagery confirmed the development of a new effusive phase beginning in April 2025, characterized by the phenomenon of apparent blue-flame emission -a visual effect produced by the combustion of sulfuric gases upon contact with atmospheric oxygen rather than a true coloration of the lava itself (Oppenheimer &

Yirgu, 2002; Fig. 4.8). These observations confirm the high temporal variability and ongoing dynamic nature of Erta Ale's volcanic system.

Scientific significance

Erta Ale provides a uniquely accessible natural laboratory for the study of persistent lava lake dynamics, basaltic magmatic processes, open-system degassing, and real-time volcanic behavior. Its lava lake system offers continuous insights into the interaction between shallow magma bodies and the surface environment, and has been the subject of sustained scientific investigation since the late 1960s (Barberi & Varet, 1970; Oppenheimer & Francis, 1997; Field et al., 2012). The volcano's position within the Afar spreading system means that its magmatic plumbing is directly connected to the broader lithospheric extension processes that make the Afar Depression globally significant.

Accessibility and visitor infrastructure

Access to Erta Ale has been significantly improved by recent road construction. The Afdera-Erta Ale junction segment of the Ahmed Ela Road Project - funded by the Ethiopian Road Authority and constructed by China WU YI Co. Ltd - now provides a paved or well-graded surface for the majority of the approach route. Despite this infrastructural improvement, visitor accommodation at the site remains extremely limited, consisting only of rudimentary wind and sun shelters constructed from volcanic rock, wood, and rope on the crater rim. This deficiency represents the most significant barrier to sustained geotourism development at Erta Ale, as the absence of overnight facilities reduces visitor dwell time and limits the economic benefit to local communities. Development of basic but appropriate accommodation infrastructure - designed in harmony with the volcanic landscape and managed by local Afar communities - is identified as a priority management action.

Geotourism assessment and significance

Erta Ale is assessed as a geosite of **international significance** and the highest geotourism priority in the volcanic landforms category. Its combination of persistent lava lake activity (one of only four globally), active volcanological dynamics, extraordinary aesthetic spectacle, high adventure value, and deep scientific significance renders it exceptional across all five assessment criteria (Vs = very high; Ve = high; Va = very high; Vah = very high; Vc = high priority). Erta Ale alone satisfies the scientific value threshold for UNESCO Global Geopark designation and represents the flagship geosite of any proposed Afar Geopark.



Figures 4.6 Active lava lakes of Erta Ale (two), seen from the south in 1968 (fumaroles; Photo J. Varet-top left); Satellite image of the Erta Ale crater, with the extent of the November–December 2010 eruption lavas (top right). Erta Ale Lava Lake, showing rise in observed lava levels (Photo D. Keir 2009-bottom left); Erta' Ale overspills (Photo L. Field, 2010-bottom right



Figures 4.7 Satellite image of the Erta Ale crater (image acquired on on 15 Aprile 2024) and field photographs showing three active cones with limited extent of lavas flown/risen (Photo Jemal, 2024).



Figures 4.8 Field photographs showing Lava Lake rise and occasionally overflow (Photo Yasin, 2025). Satellite image of the Erta Ale Volcano (satellite image acquired on 15 May 2025) and concrete road (bottom right- Afdera- Erebti junction- Ahmed Ela Road Project)

4.2.2 Awash River canyon, waterfalls and destination lake basins

Geological setting

The Awash River -the only major river originating on the Ethiopian Plateau that flows into the Afar Depression rather than toward the sea - has incised a series of dramatic canyon sections through Quaternary volcanic and sedimentary sequences as it descends from the highland margin (west of Addis Ababa) into the rift basin (Lake Abhe). The canyon walls expose a stratigraphic record of alternating basaltic lava flows, ignimbrites, tuffs, and lacustrine sediments that documents the eruptive and depositional history of the Ethiopian-Afar volcanic province across multiple timescales (Tesfaye et al., 2003).

Awash Waterfall occurs along the Awash River corridor (at Awash National Park, fig.4.9) which are controlled by lithological, (e.g. alternate strata of basalt with different strength and ignimbrite), structural (i.e. normal fault (NNE) and various sets of joints), and geomorphological factors such as weathering and erosions. The Awash River destination lake basins are known by their swampy environments, delta fan, and chain of interconnected lakes (i.e. Lake Gemeri, Afambo, Bario and Abhe) where the Awash freshwater supplies first to Lake Gemeri and overflowing into Lake Afambo and then drained to the Bario and flows down to Lake Abhe (Fig. 4.9). Lake Abhe (the last destination) lying on the border between Ethiopia and Djibouti where most part of it lyes in Ethiopia and is situated in the center of Afar Triple Junction.

Geotourism significance

Based on esthetic values such as scenery, the sideway spread water with various steps, gorges, sounds of the falls and views of crocodiles on the river bank provides wonderful pleasure and put good remembrances for visitors at Awash waterfalls (fig.4.9). The ultimate destiny of Awash River morphology, hot springs, its proximity to a spectacular Dama Ale Volcano and being an intersection place of the three rifts (Afar triple junction) make Lake Abhe one of the most fascinating areas with considerable aesthetics, scientific and economic values. The sun set activities and colonies of flamingos are also another astonishing aspects of the area. Apart from beauty, Abhe Lake could offer adventure tourism such as trekking and boat riding. The combination of river canyon scenery, waterfall features, lake formations, hot springs aspects and paleontological potential makes the Awash corridor a multi-value geosite of considerable geotourism appeal.

Geotourism assessment and significance

The Awash River canyon and waterfalls and destination lake basin system is assessed as a geosite of **national significance**, with high educational and aesthetic values (Vs = moderate; Ve = high; Va = high; Vah = moderate; Vc = medium). Its proximity to Awash National Park- a UNESCO-recognized protected area - provides an existing management framework and visitor infrastructure that could be leveraged for geotourism development with relatively modest additional investment.



Figures 4.9. Satelite image (Google image Pro) and Field photo of Awash Waterfalls

4.2.3 Tectonic and Structural Frameworks

Geological setting

Manda Hararo–Dabbahu rift segment- situated in the Central Afar Depression and represents one of the most seismically and volcanically active continental rift segments on Earth. It is the site of the most dramatic rift opening event recorded in modern geological history. The surface expression of the 2005–2010 rifting episode remains clearly visible in the landscape: fresh fault scarps, open fissure systems, lava flows emplaced during intrusion events, and hydrothermally altered zones along dike margins are all accessible to field investigation (Ayele et al., 2007; Wright et al., 2006; Fig. 4.11). These features constitute a uniquely recent and well-documented record of active continental breakup,

transforming the Manda Hararo–Dabbahu segment into a globally significant outdoor natural laboratory for tectonic geotourism.



Figure 4.10. Drone image (Google Earth) showing Lake Gemeri. The views over the swampy area from the higher ground are really astonishing during sun set time. Satellite image (Google Earth pro) and field photographs Lower Awash River morphology and Lake Abhe Hot Spring

Afar Triple Junction: it is a geological depression that developed in the area of the Triple Junction where two oceanic ridges-the Gulf of Aden and the Red Sea- (land representative), and a continental rift, the East African Rift Valley, meet-largely (fig. 4.12). The junction is confined specifically to the east central Afar Depression southwest of Lake Abhe as evidenced from DEM and satellite image. Besides its geological particularities described, it is the only place in the world where an oceanic plate boundary can be observed on land with all its successive steps of development since continental break-up.

Geotourism assessment and significance

The Manda Hararo–Dabbahu rift segment and Afar triple junction are assessed as a geosite of **international significance** with exceptional scientific and educational value (Vs = very high; Ve = very high) where its *aesthetic appeal, Adventure importance; and conservation priority is high to medium (* Va = high; Vah = high; Vc = medium). The dramatic and visible surface record of active rifting - including open fissures, fresh fault scarps, and recently emplaced lavas - provides a uniquely compelling tectonic geotourism experience with no close equivalent elsewhere on Earth at the surface. Integration with the Boina fumarole field (Section 4.1.3), located within the same rift segment, creates a coherent Northern Afar tectonic geotourism circuit of international appeal.

4.3 Paleoanthropological Localities

The Afar Depression's contribution to the science of human evolutionary origins represents a dimension of its geoheritage that is without parallel globally. The Middle Awash research area and associated localities within the Afar have produced a succession of hominin fossil discoveries spanning more than four million years of evolutionary history, establishing the region as the single most productive paleoanthropological territory on Earth. This extraordinary scientific legacy generates a geotourism proposition of genuine global significance - one that appeals not only to specialist researchers but to the broad international public fascinated by the origins of humanity.

4.3.1 Hadar: the Lucy site

Scientific significance

Hadar, located in the Central Afar Depression along the Awash River corridor, is the site of discovery of the *Australopithecus afarensis* specimen AL 288-1 - popularly known as Lucy -recovered by Donald Johanson and colleagues in 1974 (Johanson et al., 1982). At approximately 3.2 million years of age, Lucy remains one of the most complete and most studied early hominin specimens in the fossil record, and her discovery fundamentally altered scientific understanding of bipedal locomotion and the phylogenetic relationships of early hominins. Hadar has subsequently yielded additional *A. afarensis* specimens, including the "First Family" assemblage representing at least thirteen individuals of varying age and sex (Johanson & White, 1979).

The Hadar Formation - a sequence of lacustrine, fluvial, and volcanic sediments exposed along the Awash River valley - constitutes the geological context for these discoveries and itself represents a site of significant stratigraphic and paleoenvironmental interest. The interbedded tephras provide radiometric age anchors for the hominin-bearing levels and document the environmental backdrop of early hominin evolution in a dynamic rift basin setting (fig. 4.13).



Figure 4.11 Filed photograph of the recent open fissure systems in the Dabahu-Boina area and drone image of an open extensional fissures/fractures and an impressive *Loma Lake* pit crater within the Manda Hararo rift segment, Central Afar Depression.

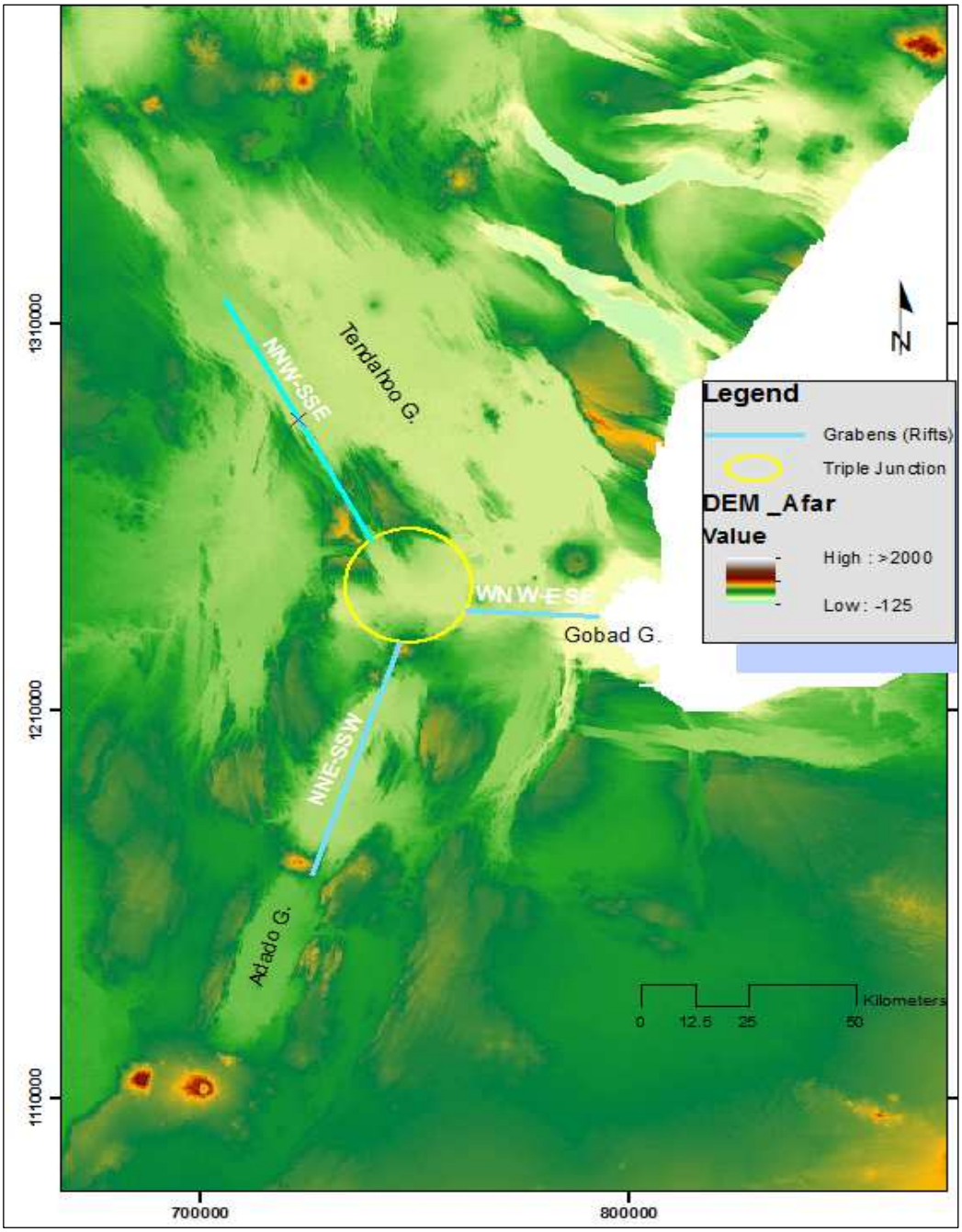


Figure 4.12 Afar Triple Junction in the east Central Afar Depression (the yellow circle is the converging zone a three land representative normal faults

Geotourism significance

The name "Lucy" carries global recognition far exceeding the specialist paleoanthropological community, providing an immediate and powerful geotourism narrative. Visitors to Hadar encounter not only the landscape where one of humanity's most famous ancestors was found, but also the active geological processes - river erosion, sediment exposure, volcanic tuff outcrop - that continue to bring fossil material to the surface. The site's proximity to the Yangudi National Park and Tio geothermal field further enhances its geotourism development potential through ecosystem-level integration and geothermal features.

Geotourism assessment and significance

Hadar is assessed as a geosite of **international significance** with exceptional scientific and educational value (Vs = very high; Ve = very high; Va = moderate; Vah = moderate; Vc = high priority). Its primary geoconservation challenge is the protection of fossiliferous surfaces from uncontrolled visitor access and surface disturbance, requiring zoned visitor management and trained local guide programs.

5. Discussion

5.1 Geotourism potential in a global and African context

The systematic geoheritage assessment presented in this study confirms that the Afar Depression hosts a concentration of world-class geosites with no close equivalent on the African continent. Of the fourteen principal geosites inventoried, six were classified as international significant, collectively spanning geothermal, volcanic, geomorphological, paleoanthropological, and tectonic categories. This thematic breadth - encompassing both abiotic geodiversity and associated cultural and evolutionary heritage - distinguishes the Afar Depression from most existing UNESCO Global Geoparks, which typically derive their designation from a narrower range of geological phenomena (Brilha, 2016; UNESCO, 2016).

Africa's representation within the UNESCO Global Geoparks Network (GGN) remains dramatically disproportionate to the continent's geological significance. As of 2026, fewer than three African geoparks hold UNESCO designation, compared to more than 100 in Europe and East Asia (GGN, 2026). Ethiopia, despite possessing one of the highest concentrations of UNESCO World Heritage Sites in sub-Saharan Africa, has yet to establish a nationally recognized geopark. This study's findings provide the first systematic, multi-criteria evidence base to support Ethiopia's advancement toward geopark development, with the Afar Depression emerging as the highest-priority candidate territory.



Figure 4.13 Heritage sites of Lucy and morphology of Ada-A'r/Hadar Formations

5.2 Flagship geosites and UNESCO GGN candidacy

The assessment identifies Dallol hydrothermal field and Erta Ale shield volcano as the two flagship geosites of any proposed Afar Geopark, both achieving the highest composite geotourism potential scores across all five evaluation criteria. Dallol's status as a globally unique hyperacidic hydrothermal system with documented astrobiology significance (Cavalazzi et al., 2019) and Erta Ale's position as one of only four persistent lava lake systems globally (Field et al., 2012) individually satisfy the scientific value threshold for UNESCO GGN designation. Together, they represent a scientific asset of extraordinary international significance.

The Middle Awash paleoanthropological corridor - encompassing the Ardi, Lucy, and Gona localities - adds a dimension of geoheritage value that extends beyond conventional geological criteria, incorporating more than four million years of hominin evolutionary history within a single geographically coherent territory (Johanson et al., 1982; White et al., 2009; Semaw et al., 2003). This paleoanthropological legacy creates a geotourism narrative of global public appeal that would distinguish the Afar Geopark from all existing African geopark designations.

The Manda Hararo-Dabbahu rift segment and Afar Triple Junction provide a third globally significant scientific asset - a real-time, instrumentally documented record of active continental rifting (Ayele et al., 2007; Wright et al., 2006) - that reinforces the Afar Depression's claim to the status of the world's premier natural laboratory for Earth science education and research.

5.3 Geo-health dimension: an emerging geotourism value

A distinctive finding of this study is the dual geo-health significance of the Afar Depression's geothermal features - simultaneously offering traditional therapeutic value through balneotherapy and presenting documented public health risks through geochemically hazardous drinking water. The detection of arsenic, fluoride, and mercury concentrations far exceeding WHO guidelines at Alallobad, Tio, and Boina (Section 4.1) underscores the urgency of geochemical risk communication as an integrated component of any geotourism management framework. This finding aligns with the growing recognition of geo-health as a legitimate and important dimension of geoheritage value, while simultaneously highlighting a management responsibility that extends beyond visitor experience into community health protection.

5.4 Geoconservation challenges

The Afar Depression's geosites face a range of geoconservation threats that must be addressed within any geopark management framework. At Dallol, the fragility of evaporite surface structures -including halite terraces, salt flowers, and brine pool margins - renders them vulnerable to physical disturbance by unregulated vehicle access and on-foot visitor traffic. At the paleoanthropological localities, fossiliferous surfaces require protection from collection and surface

disturbance, necessitating zoned access management and trained local guide programs. At volcanic sites including Erta Ale and Boina, visitor safety from degassing, unstable ground, and eruptive activity requires formal risk assessment and management protocols that currently do not exist.These challenges are not unique to Afar - comparable geoconservation management issues are well documented in emerging geopark territories across Africa and globally (Ngwira, 2015; Errami et al., 2013).

5.5 Community participation and sustainable development

The long-term sustainability of geotourism in the Afar Depression is contingent on the meaningful participation of the Afar pastoral communities as active stakeholders and economic beneficiaries rather than passive recipients of externally driven development. The geo-cultural heritage of traditional salt production on the Danakil plains/lakes, traditional geothermal therapy at Alallobad and Tio, and Afar ecological knowledge of the volcanic landscape all represent community assets that can be integrated into a geotourism offering of exceptional authenticity. International experience demonstrates that community-managed geotourism generates more durable conservation outcomes and greater local economic benefit than externally managed models (Farsani et al., 2012; Ngwira, 2015).

6: Conclusion

This study presents the first systematic, multi-criteria geoheritage assessment of the Afar Depression, northeastern Ethiopia, integrating field investigation, satellite imagery analysis, hydrochemical sampling, and comprehensive literature review across a four-year research program (2021–2024). Eleven principal geoheritage sites were identified and inventoried across five thematic categories-geothermal features, volcanic landforms, geomorphological landscapes, paleoanthropological localities, and tectonic phenomena and evaluated using an integrated five-criterion assessment framework encompassing scientific, educational, aesthetic, adventure, and geo-health values.

Six geosites were classified as globally significant, five as nationally significant, and two as locally significant. Dallol hydrothermal field, Erta Ale shield volcano, Allalobad and Boina geothermal, the Middle Awash paleoanthropological corridor-Hadar, the Manda Hararo–Dabbahu rift segment, and the Afar Triple Junction collectively represent a concentration of world-class geoheritage assets with no close equivalent on the African continent. Three geosites - Dallol, Erta Ale, and the Middle Awash corridor - individually satisfy the scientific value threshold for UNESCO Global Geopark designation, and together constitute a flagship geopark core of exceptional international significance.

Spatial analysis revealed three coherent geoheritage clusters - Northern Afar, Central Afar, and the Middle Awash corridor - providing a natural framework for geopark boundary delineation and zoned management. Despite Ethiopia's outstanding concentration of UNESCO World Heritage Sites, no national or UNESCO Global Geopark has yet been established in the country. This study provides the scientific foundation and site inventory to initiate that process for the Afar Depression.

The integration of geotourism into geopark development in Afar has the potential to simultaneously advance geoconservation, expand geoeducation, generate sustainable livelihoods for Afar pastoral communities, and position Ethiopia as a significant contributor to the UNESCO Global Geoparks Network in Africa. Realizing this potential requires coordinated action across scientific, governmental, community, and international institutional actors.

Acknowledgements The authors gratefully acknowledge the logistical support of the Afar Regional Bureau of Tourism. Field assistance provided by Afar community guides and research assistants is gratefully acknowledged. Water sample analysis was conducted at the Ethiopian Construction, Design, and Works Corporation laboratory, Addis Ababa.

Author Contributions Jamal Ahmed: Conceptualization, geosite assessment and its interpretation Writing-Original Draft, Project Administration. Mohamed Kedir and Salih Usman: field survey, Writing - Review & Editing. Abdu Ahmed: Resources, Stakeholder Engagement, Writing - Review & Editing. All authors approved the final manuscript.

Declaration of Competing Interests The authors declare no competing financial or personal interests that could have influenced this work.

Funding This study was carried out as part of the Geotourism Project funded by Samara University (Contract No. 2023-9-SU.0).

Declaration of Generative AI The authors declare that no generative artificial intelligence tools were used in the preparation of this manuscript. Artificial intelligence (Al) tools were used to refine the language, grammar, clarity and reliability of the manuscript.

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